Compliant Mechanisms: Principles and Design
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Lecture - 31
YinSyn; synthesis of non-linear responses with compliant mechanisms

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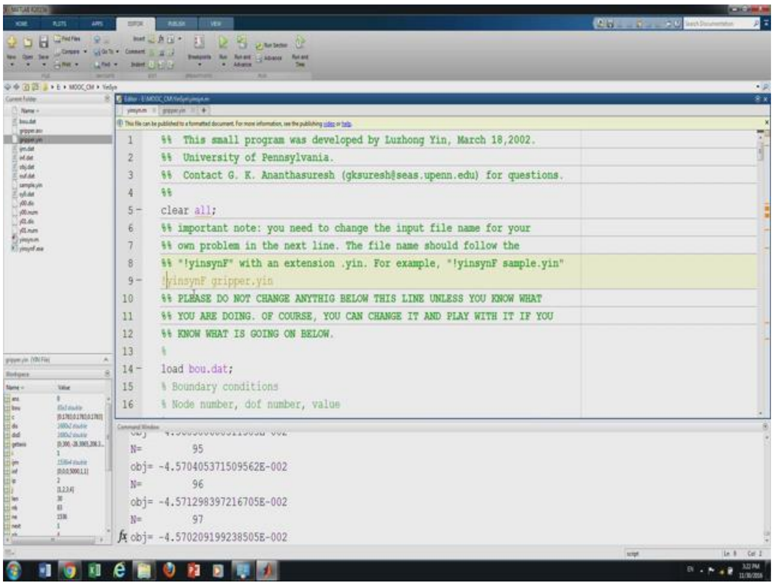

Hello, in this lecture, actually it is not a lecture it is a demonstration or lecture demonstration, where we are going to see how optimality criteria method can be implemented to obtain compliant mechanism topologies based on what we discussed in the lectures. This program was written by my post (Refer Time: 00:39) luzhong yin way back in 2002, even the date I have put there and that still works in the sense that after many years in math lab we are able to still use that thing. It was actually written in Fortran, but we have a mex file implement in mat lab and it works as operating systems are changing still this seems to be working compiled many years ago more than you know 14 years ago.

So, this particular one requires in input file that is in this case, I have an input file called gripper dot yin. In fact, yin is because his last name it is input file or luzhong input file and that is all we need to create an input file for the specification that you are interested in you look at the input file now, once you do that you do not have to touch the rest of the mat lab code or the fortran code that is yinsynF, yinsyn because Luzhong yin synthesis problem yinsyn fortran with exclamations that runs that fortran file executable file is there in the folder you will have that executable file as well as sample input files and the mat lab program.

So, these are three things that you need and you can run it, as a supplementary file for this course you will have these to run you can also download from my website at iic. So, we will run this now and then see how we get the solution. First let me run so we are running it you can see iteration number 1, 2, 3, objective function, which is negative that ratio of negative MSE by SE. So, it keeps on decreasing meaning that it becoming more and more negative as you can see minus 4.54 minus 0.55 it is going there, it will converge after some iteration or we interrupt it is after 100 iterations usually that is good enough. In fact, 50 iterations are good enough for enough algorithms for this optimality criteria method to work here it is done.

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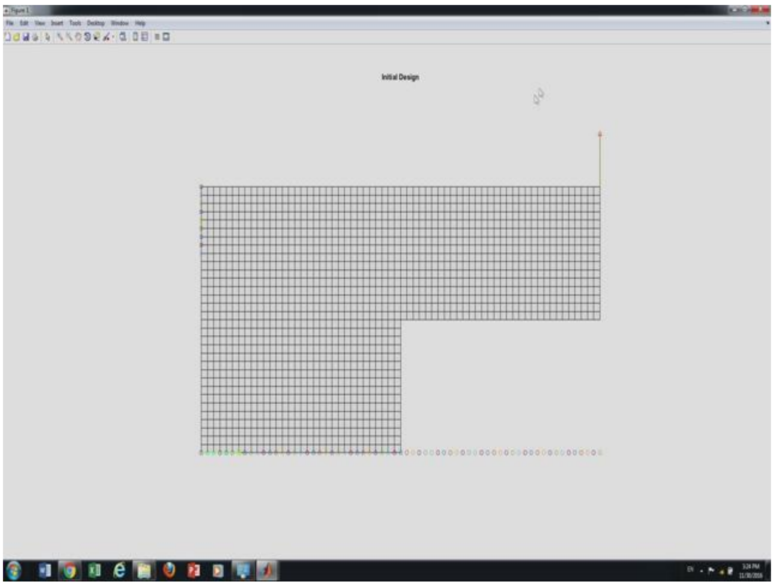

It went it took all the 100 iterations now it is giving the solution. So, you can see what we have put here. So, let us look at the specification we have taken a domain where there is a hole already meaning that is a l shaped domain, we have taken a big rectangle and subtracted a smaller rectangle our boundary conditions are that this edge here is fixed. Meaning that both x and y degrees of freedom are fixed it is a 2d implementation not a 3d, 2d everything is claner this is fixed here, and the bottom edge here is symmetric like a roller boundary condition all the points here can only move in this horizontal or x direction, but cannot move in y direction meaning that if I take a mirror image will be symmetric, which a symmetric boundary conditions here we are applying a force here where applying a force there and we want this point to move out like that.

So, basically where I push here they should open up like this and the other side if a mirror image it will also go the other way right, that is the specification again you are fixing it here and this. So, with this one we get a topology solution that looks like this so let me make it bigger.

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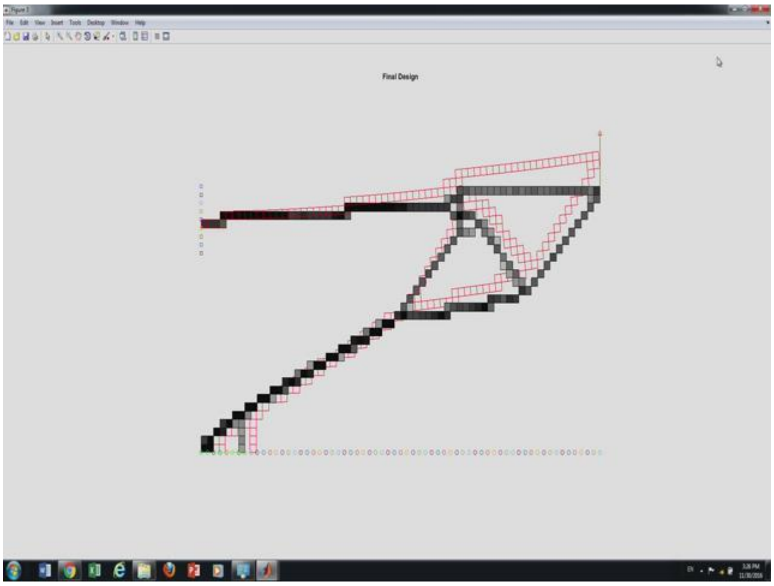

So, it is fixed here roller support here that was circles and this is squares that is fixed and we are applying a force not over there I am applying a force here, you can change it to that place also applying a force in this lower left corner apply a force they should move out. And you gave a very small volume so lots of elements are gray color, so black here means that rho is equal to 1 material is present lot of things have disappeared from a design domain here, that is all has gone to rho equal to 0 in between there are a few giving a small volume I will show you what volume are constraint we have, then you will actually get a skeleton type of structure now when you have this it actually works.

So, if I look at super imposed with the displacement we get solution like this you know that is that is apply a force here, it is going to move out we can see that if there is a slender beam element there and little triangle over here another triangle meaning that it is a rigid body can apply a force it goes like that right. So, it could be intuitive for some you, so if you try that yourself you might obtain the same solution from your mind from your intuition, but here we just get the solution. So, here I have now five students of mine were IIC students. So, they should be very smart, I ask them to do this problem.

Let us see what they would had from there intuition. So, I would ask anyone of them to come forward and show their solutions. So, we can compare what they have verses what the algorithm gave.

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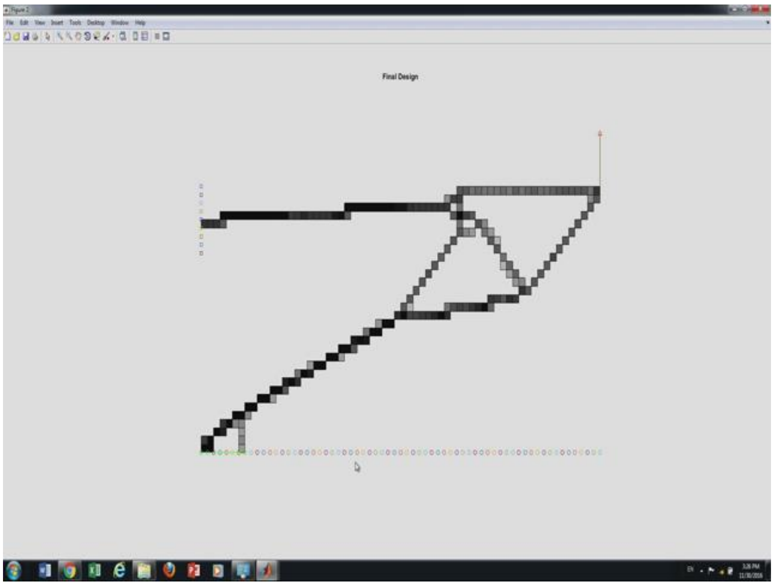

So, for this specification, so anyone of you can come and show your solution so again it is fixed here and this is a roller support.

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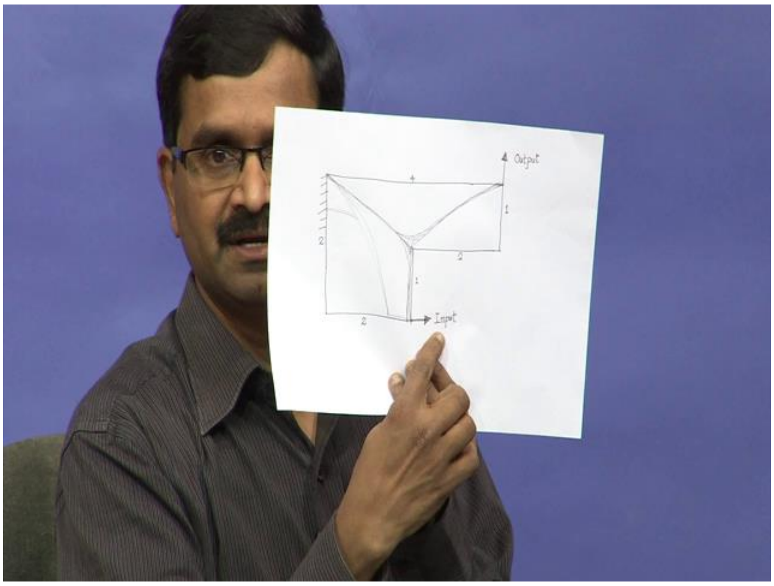

Let us see what solution in this case the input is over here as in this way and output is there. So, whereas, this algorithm has input there we will change it. So, the solution that one of my students Surfan Palathingal has got in this because it is fixed here, he has got in that and this is a vertical thing and when you apply the force like this you think it is goes up like that, now the difference is that the one that we ran have applying the force here. So, it together in client one rest of it is all rigid.

So, you also have put some fill it type of thing here, whereas; here it is little bit more and he has made this is part of the solution safran no. So, solution is only this here right just three beams he things that if apply that whether it is correct or not we have to do finite element analysis and find out, but now we just looking at it. Now let us me move that force from here to here and then see what the algorithm does. Let us go back to the code and look at the input file that gripper dot yin, which I have here is a text file, it is self explanatory.

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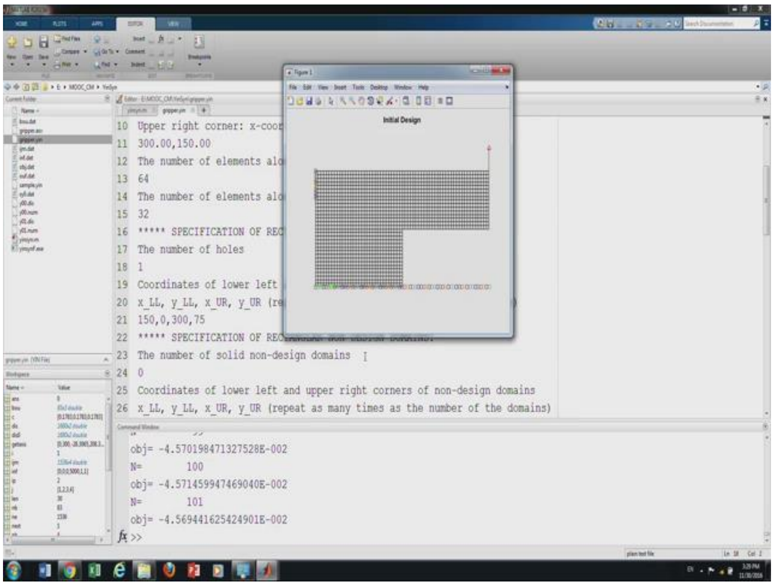

First says worker element type you want to use there is c 0 for finite element input and then c 1 for finite element you know input if you want to c 0 continuity c 1 continuity, here using c 0 continuity, let us not going to the detail of what is c 1 continuity finite element. And then if you put mech here we have solving mechanism problem, if you put s t r u, you can actually do stiff structure problem, because this algorithm is identical in many ways to stiff structure of optimization you can put stiff structure is s t r u or mech for compliant mechanism and you can define the rectangular domain sorry, the 2 by defer the lower left corner and then upper right corner you have defining a rectangle and then number of elements along the x direction and y direction. So, since in 300, 150 2 half all the elements square elements is always preferable, we have 64 along the x axis 300 units and then 32 for the 150 units we can change it a number of holes we have put one hole to takeoff that little thing the right side.

So, that is let me just show that you are with me, so this is the hole. We have big rectangle 0 0 300 300 and then you have a small hole that goes from 150 to 150 0 that is this point and then 300 75 that point that is why we can define lower left corner upper right corner we can put a hole we can put a hole inside also if you want. That is what we have and then number of solid non design domain, sometimes you may want to put material somewhere for sure. So, here we are not putting material anywhere, but that is what is 0 otherwise you say 1 and you can say from here to here I want to have black meaning material should be there, that also can be given that is called non designed domains and number of edges where you want to specify displacements this not condition you have 2 edges.

Again let us see what those 2 edges are, 1 edge is that and other edge is this. Edge you can give from again starting point ending point they can also be inclined if you want, because starting point here ending point there you can fix that it is a very general a program of course, without users interferes that is for a reason because when you want a code to last for a long time if you put user interface as a version of the program changes mat lab things will change.

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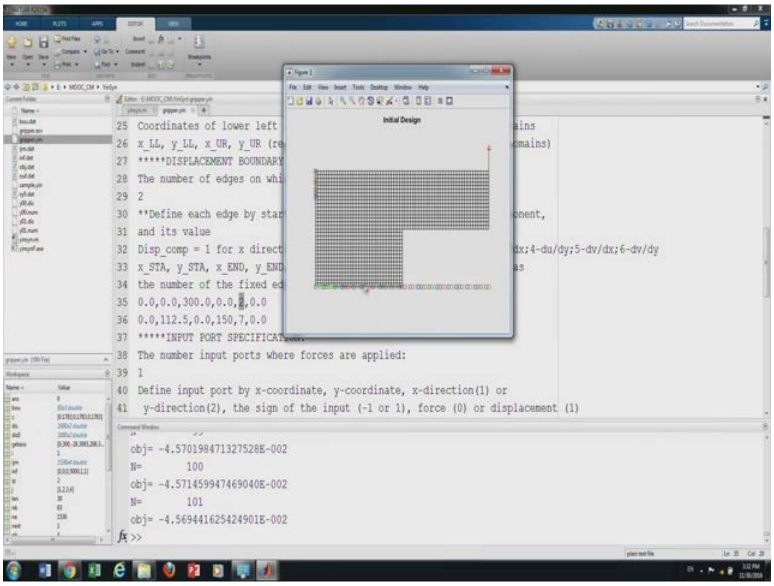

So, here we just have a text version. Here we have 2 edges and we give the 2 edges. So, he says x starting point, y starting point, and then x end y end and displacement component that you want to fix, whether it is you know x degree of a y degree of freedom where it says if it is x degree of freedom 1 y degree of freedom 2 and both of them 7, there are other 7 continuous element ignore that ignore this part 3, 4, 5, 6. So, 1 is for x, 2 for y, 7 for both, so for one thing we are fixing both that is the left side top edge that we have. So, that is this one, we are starting from 0 112 something 112.5 to 150 those are the once we are fixing both degrees of freedom that is why it is 7, and in the horizontal 0 0 that is 0 0 300 0 that is this point everywhere we have roller support

Even though there is a hole we are still doing it that does not matter for the program, because it is not complaining and then we have second 2, 2 meaning that y direction is to be 0 meaning that you have a roller support and things cannot move in the y direction symmetry boundary condition, that is what we have and then we also have the input port that is where the forces applied we have only one of them you can have as when as he want and again the x coordinate and then y coordinate, that is what we have and then 1 1.

So, this one is what is the direction 1 is x, 2 is y and then sign, whether it towards positive side and negative side and then if it is force it is 0 displacement it is 1 here is a force, we have 0 then 5000 is the magnitude, how much force you are applying. We were applying the force at 0 0 that is what I had said that why I am applying force here instead lets moving to 150. So, let me put the force here 150 now the force point has moved let me save it, so force point has moved from here to here 150 is the x coordinate 0 the y co ordinate and again it is still in the same direction.

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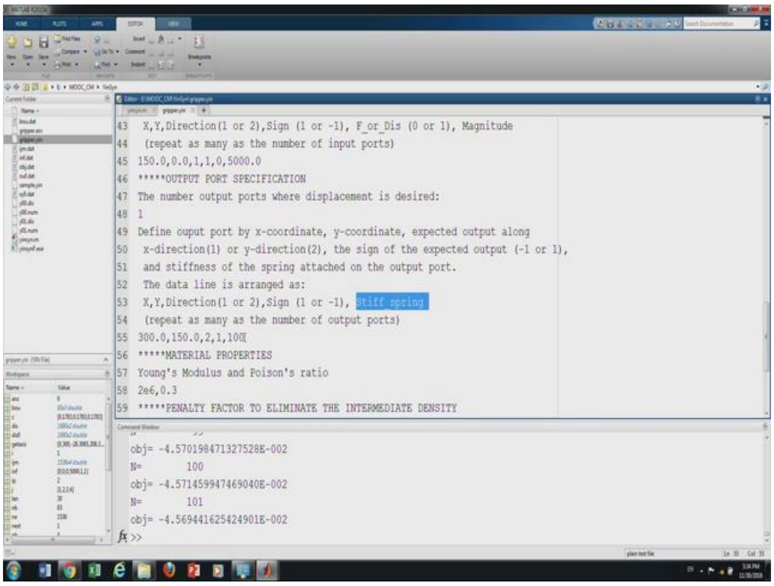

And output also we have only one point you can have multiple, but one make sense for as will be start out, and where is it? It is 300 150 meaning it is the upper right corner and again it is 2 second degree of freedom positive direction, and we have 100 as the stiffness of the spring we will come back to this notion without spring this algorithm will not give a solution all the time right, now the way is implemented you can try whatever you give you get a solution as long as input is consistent that is you are not put a output point in the place where there is a hole and things like that. So, if you give proper input it will give a solution always the stiffness of the spring is important that is output point needs to have a load.

We will come to that in the next lectures we have that 100 here, and material property we are taking youngs modulus some 2 mega pascal number actually does not matter for topology (Refer Time: 14:17) we show taken point 3 that matters a little bit, but not a whole lot and then this penalty factor that eta that we discussed in the lecture d equal to rho raise to eta times d 0, that this eta to be taken 3 here you can try what happens if you change it and then volume fraction here we have put point one meaning it is fraction 10 percent that is why it is very lean, we will change it and rerun it and lower and upper bounds 0.01 is lower bound 1 is the upper bound that rho has to vary between 0 and 1, here it is 0.01 and then 1 you know that 0.01 and raise to 3 will be 10 power minus 6. So, this close to 0 and then tolerance for stopping that is rho k plus 1 and rho k 10 powers minus 5 pretty type tolerances.

These what we have let us save this and run the program again it is running real time in mat lab meaning that if you do it in see a fortran directly you would be much faster of course, it is a running frotran program here on this platform you can see iteration numbers are just going if you make it very fine tune not more elements.

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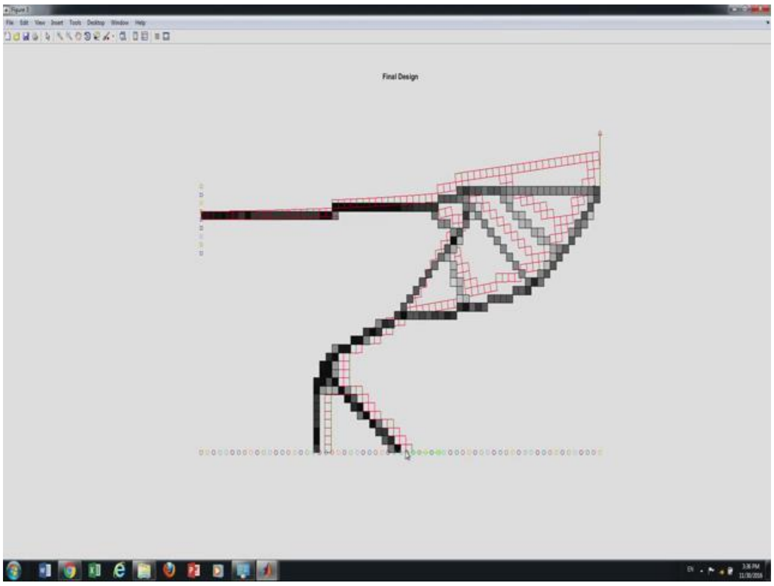

Then it will be little slower because you have 2 finite element analysis that teach iteration now it is done and it got a solution see it just moved previous we were applying there, now it has moved it over here these were applying the force now compare to what my student did where he has taken directly from here to somewhere there and you got it down something like this. Now this is taking little bit of a rigid triangle here I said triangle become the symmetric boundary conditions, it is like a rigid body is there the whole thing can move right and it is of course, applied there and it is going like this, this is coming and it is going like that.

Slightly different topologically one can argue it is a same, because these all after all it is rigid, he went from here to here and got that one and then made it this move like that right. Now, idea is that we can do intuitively, but we can also do it very quick using algorithm now instead of going up like that, now I ask the students to think about what happens if I want these two come this way to the left algorithm is say easy think for metric file. So, I am applying the force over here and I want this point to move to the left like this; what happens? Let us run this before I do that just.

So, that they have little bit more time to do that is output now should not go up it should go to the left everything else remain the same, now what will do is first we will increase the volume a little bit and then see what happens instead of 10 percent let me actually make it that is a 30 percent on the material alright.

Let us see if the topology remains the same to for you to see that what I will do is save one of these pictures so that you can compare. So, let me take a screen shot and save it somewhere or now, we can compare that is paste here I think screen shot has to work let me get the solution you can screened let save that. Now let us go and re-run this I hope I saved it we were saved it 30 percent material let us see how the topology changes when you have more material, everything else is the same now from previous time we ran it only thing is material we are giving 30 percent rather than 10 percent we have to given that was the very lean design where we can actually see the skeleton very clearly now it will be fatty one.

Where you cannot see the inherent characteristic, but the topology whether it similar or changes we can look at it again it is real time it is time to you know minimize the ratio that we talked about subject to the volume constraint that we have it is done now. So, show the solution it is going to change it is plotting.

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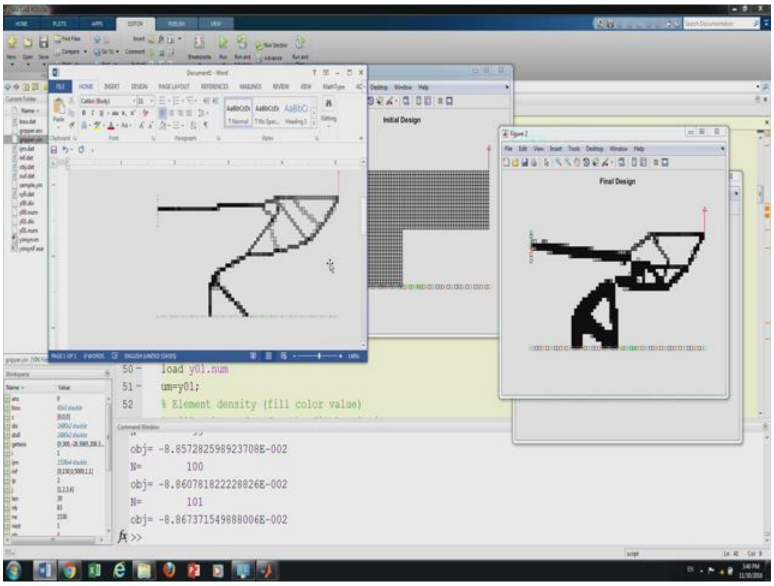

Now let is compare what we got over here verses what we got with 10 percent. So, topologically they are the same, because this particular thing is (Refer Time: 19:47) a little bit and instead of using the slender beam here, it has now gotten a flexural hinge we will come back to the another lecture it is a very important thing where does it go for a hinge here and this beam here is little fattened we have more food for it, because we gave more volume and again it has a flexure here, whereas; here it was like more distributed and then rest of it topologically it is similar that is what we got. So, when you sometimes give a lot of volume you do not see the essence of the topology when you give very little volume you can actually see beam elements or beam segments emerging out of it.

Now, what will do is we will go back to 10 percent and change the output direction, where is output direction output fort specifications where we said it is second degree of freedom y should go up, now I will change it to one that becomes the x degree of freedom I want it to go to the left that will become minus. So, as she made 2 changes now volume as under the output point let me save it and re-run this that is he what we have now we are going to the left if anybody has tried it they will show and you can also try when the program is running test your intuition or pause it take your time and see what algorithm comes up with it is finished.

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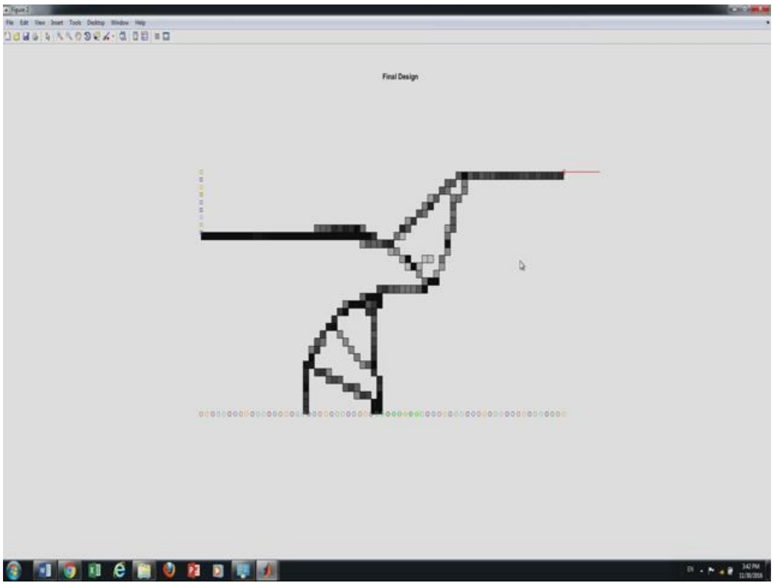

So, now it has done it is job all ready that it came up with a topology like this now what are we doing applying a force here we want this point to move that way instead of a component in that direction not saying that exactly it should moving that if you say exactly should move you put a constrain that it cannot have y displacement which you have not done. So, when this point moves it will have a component in the left direction.

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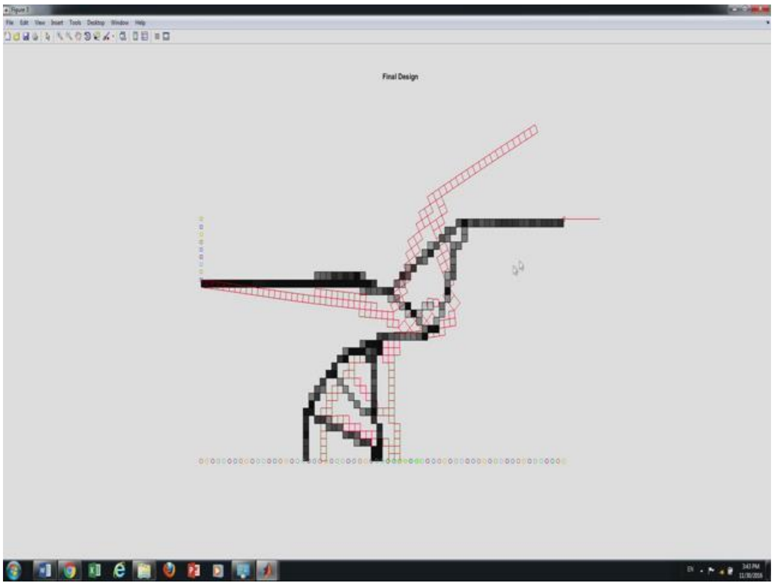

What it has done? So, we can see here where the deformed plot is also given this is while moving to the left it also has moved up, we did not constrain it that is why it does not do that if you want to constrain it you have to physically put a constrain, but that is not allowed. So, you have to put a constraint in the formulation itself. So, we can make the compliant mechanism formulation more and more difficult I am not saying that I should get a roller here. So, that it only moves in the x direction that we change the boundary condition instead I want a design where without any constrain here it should move purely in the x direction if you want that then you should say that why this place had that point is 0 and you have put a constraint a optimization and solve another non-linear constraint people have done that, but this program does not have that now it is also moving in this direction has anybody is done this to compare.

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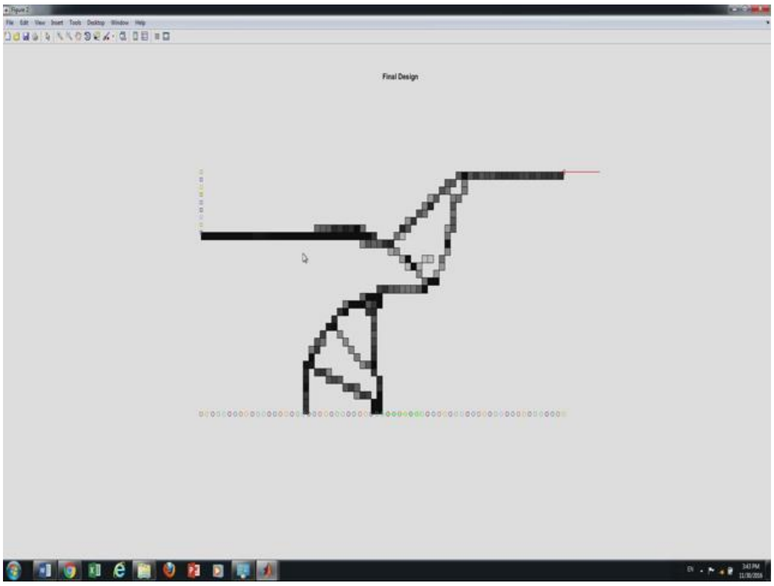

So, let us look at Anusha Pais design for this. So, had design may be read to zoom in a little bit here, where applying a force this way and she things that look at this look at this.

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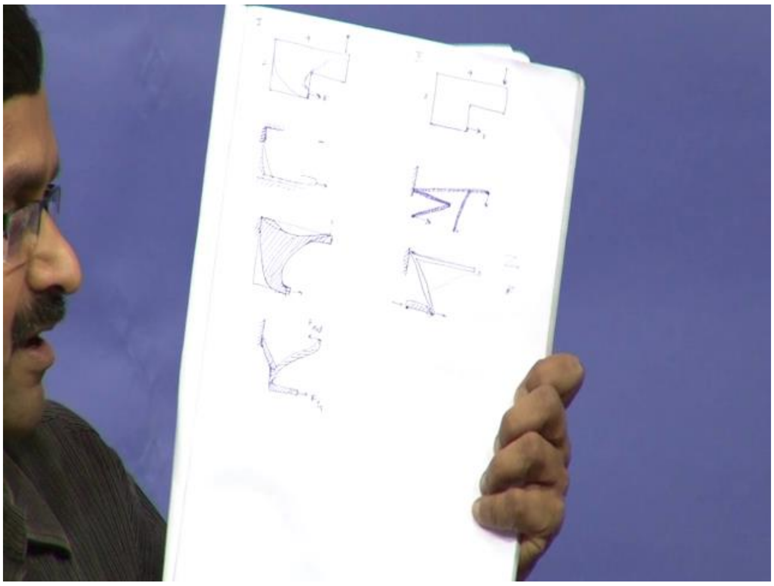

So, it is fixed over here and these all rolling boundary conditions, when apply a force here this moves like that. So, intuition tells her that when she moves it this way it is going to move like that may be your intuition also says, but finally, the sanity check would be a finite element analysis whether finite element analysis will tell when you do this it goes like that may be she have an exclamation has to why she came up with this right.

Now, we compare with what we have there topologically it is hard to say, because the algorithm if you see let us compare with what the algorithm has this point over there just as she has taken, she also has taken the lower edge to be the support and then there is this portion which is vertical which is this also has it goes like that up and it comes may be it is kind of similar, right. Because if you say that these all what she has taken as just one segment it may be right. So, we can you can look at that.

So, now will immediately change this now what if I wanted to go that way or what it goes down let us try that one more change here. So, I will say that now the point has to move down so let me go back to the input file. So, I will go back to the y displacement this is the output ports specification I go back to y degree of freedom and then say it has to come down previously we have ask you to go up now come down let us see what we get saved it let it run.

And will run it with final discretization will change the volume and saw that there is not much effect in terms of topology, now you can also make it finer and finer where it will be. So, fine that you can take it and 3d printed today that is it is possible to do that started do image processing up there is and you know 3d print that was the idea which topology optimization you do not have to give algorithm anything other than the specifications it figures out everything gives a solution.

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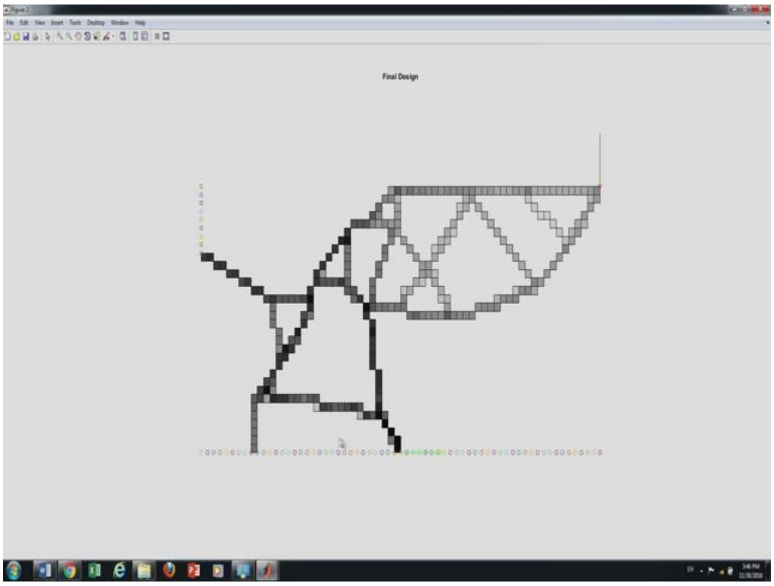

But there are new answers you know the point may not really move strictly in the y direction as we saw in this example, it is going to change the images it came up with an image. So, which looks a little complicated, but one can argue why does in a particular way which we are applying the force here it took another support like last time fixed here, and then now this point is moving down let us see if I enlarge it here you can see that it is indeed moving down it has a little x displacement also and let us see what one of the students has come up with.

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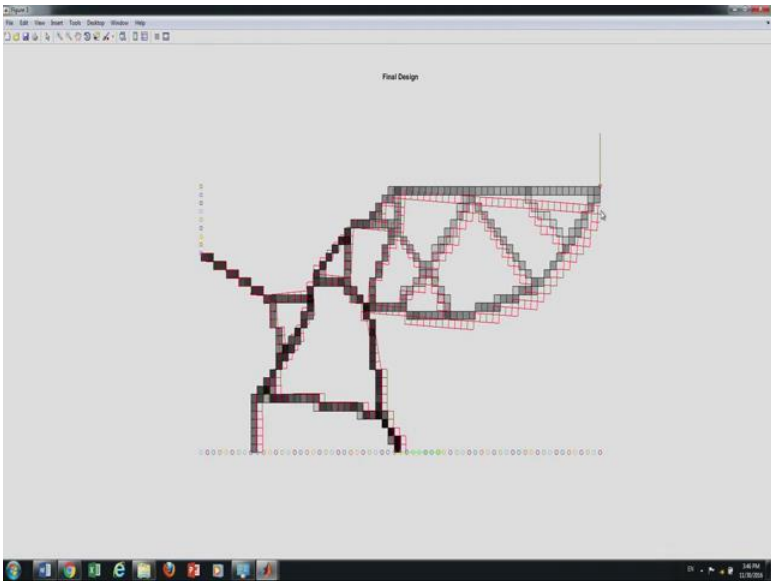

So, study the solution is little complicated it has taken lot of segments where as the one that Surfan PhD. student came with is this where we have fixed here algorithm also has take a lower edge just as he has taken. So, he has algorithm this hat and applies the force here and this has to come down.

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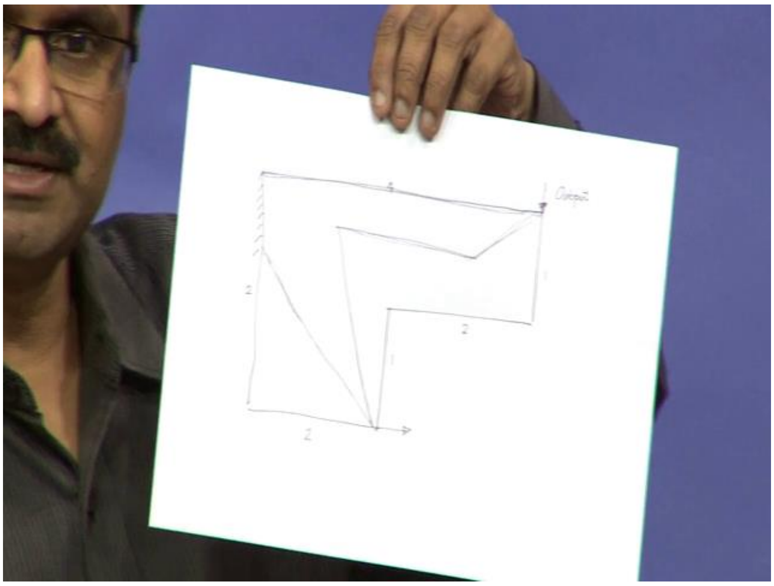

So, he has taken this and that and that I do not know why this particular shape, I am sure he has a reason for it. So, he thiks that if you apply the force here this is going to come down here is really no restriction here sometimes you know some point may not even move right.

But here I am presuming that he has taken this segment also, so that the segment is from here to here to here this particular shape of the segment he has some reasoning. In fact, he has some reasoning similarly you may have your own reasoning when you do this which is going come down is what he is thinking algorithm did not take this segment over there it actually took from here created a complicated loop and took another support back here as you can see the thing.

Sometimes may agree with your intuition sometime it does not, but every time it give a solution. In fact, we can take this and put in all direction and then see what happens. Now, what I will do is will try to make this with much finer discretization to see what happens. So, I go back to the input file and we have we can see also how fast it has right. So, we have 64 elements and 32 let me make it 128 elements and these as 64 elements that are a lot of variables in the variables are 128 by 64 since, in mat lab you can get that number 128 times 64. So, we have 8192 variables here, rho 1 rho 2 rho 81 92 let us run this.

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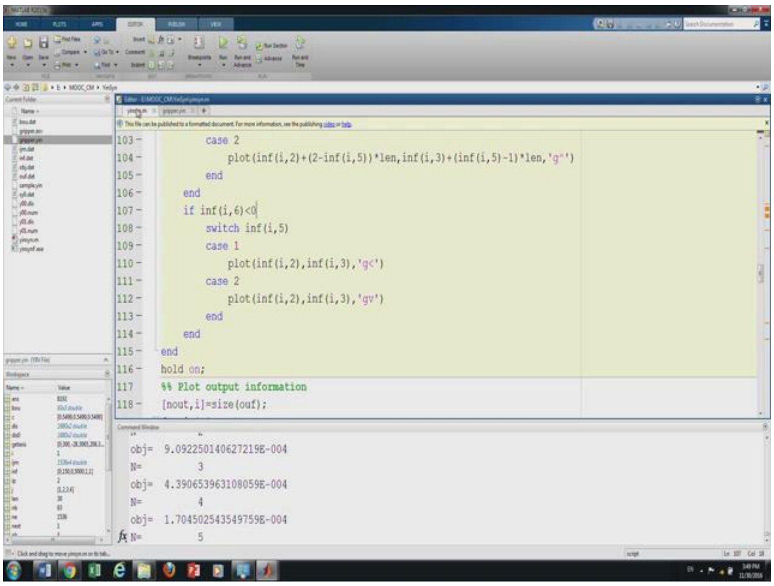

Now, let us save this and run this, now it is going take a while now as you can see because finite element analysis the one that takes more time to run it is a first iteration you can see that it taking time right (Refer Time: 29:06) does a zipping through 100 by takes a little bit of time while it is running let us look at the a input file output file one more time. So, we can again identify some of other features that we need to discuss one is this stiffness of the spring (Refer Time: 29:32) output.

Here if you do not have that spring constant then you have a lot of points in our design domain if you do not put a spring what makes the output points special, we have input points where there is a force and the algorithm knows that where the force is applied it knows meaning that it has obligation or mechanic such that it has to connect to that point. Whereas, if you do not put an output load or output spring, then the point that you have in mind is not any special compare to any other point. So, algorithm may or may not may connection to that point which will do by decreasing the spring constant this number is arrived at by playing with wherever we have put the numbers here let see instead of 100 i put point 1, then it may not even make a an attempt to connect the output point because that output point is same as any other point on the boundary are inside right there is nothing special about the output point.

So, we need to have a stiffness spring in this ratio formulation which I did not mention the lecture, but that is a practical aspect there are many other ways to achieve the same thing. So, first thing is that it is a compliant and stiffness formulation that is one thing that is we are maximizing the output displacement and trying to minimize the strain energy are higher upper bound on the strain energy. Additionally you also need to have an output load or an output spring, because a compliant mechanism the output will always against, act against some a loading or a spring load like an object elastic object or this.

But there could be problems were there is neither outputs springs nor output load how do you do that like a rigid body linkages we can also pose this. So, to avoid this need for the spring constant there are been attempts to get different formulations which will discuss in one of the lectures, but you have note that, that is an important thing other than that everything else is very straight forward here you have to defined the design domains and put a holes there what adjust you want to fix and what is the material that you want to give at the penalty factor you can play with that penalty factor we can reduce it increase it and then see and tolerance you can do it will go little faster now it all just talking were still the forty third iteration.

You going to take little bit more time he can keep on doing it now we had a originally we had 64 at 32 elements, now I put 128 and 64 if you want you can make it 256 and 128 push the limit of your memory. So, or whatever is code in this fortran file right, we can right now either 8000 variables and you can see iteration it is just taking a few seconds it is slower than what it was for course discretization, but still not bad each iteration you should know that we are doing 2 finite element analysis one with the real load applied load that we have other with the unit virtual load.

So, that is how the time is going not in the updating and the inner loop to determine this lambda and gamma right. So, all of that is happening as when it goes from let say 56 to 57, 2 finite element analysis at the update to find the to satisfy the volume constraint here which is just linear. In fact, here we do not have lambda and gamma we only have lambda corresponds to the volume constraint and you can challenge yourself by creating very complicated specification here and so for I have not seen a case where the input is consistent the solution was not obtained, if you have a problem were you not getting a design you should send that input file to me. Right now this is gripper dot yin we can save it whatever name and all if you do is in mat lab file you have to just put the name of that file.

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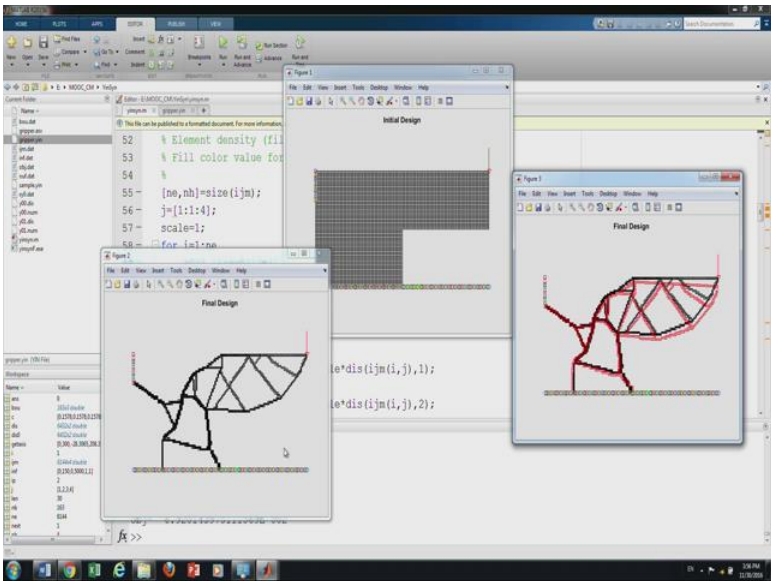

So, over here we need to just put the name of the file everything else is just reading the input or actually the when you run the fortran code by reading input file here, will generate a lot of output files this boundary condition some output input specifications and lots of other data, all that is used in this mat lab program simply to plotted it is most like a post processing thing if you look at the data here. So, if I just go let see, let it run. So, we can see the data files that will lot of these data files that are created when it execute this a thing your input file holds the key you are nearing 95 it is let go to 100 iterations. So, 96, 97, 98, 99, 100, goes 101 because first one is not counted and we get the solution it took a little longer, because we made a finer discretization it is going to plot it in a minute or less than that plot move to plot even plotting is now slow down.

So, again specifications are applying a force and it should it come down that is what we have asked, it is done now the final discretization can see and this has plotted. Now if you see we can go to little finer and actually see this there is know I mean some of these things will go away the gray ones will go or it will be a weak mesh there we have beam, we have beam, we have a beam, we have beam, we can actually put beam segments, somewhere here it is still wants to go for a hinge will talk about that there are 2 element are diagonally connecting here it wants a hinge here, a flexural joint rest of it is there and the topology has in changed, but what about we had earlier we did not save it, but you can run it again and if you apply the force there it is coming down.

So, I take only one example, but encourage to run a lot of examples all it to do is go with this input file and change it and once again when you try something any specification and you do not get a solution it is not need, because suppose to work all the time it is been working for you know dozen years or more, but make sure that your input file is consistent again if you put a hole here do not ask for output displacement there apply input force there such things you have to check when you give the specifications for it.

All these files will be available to you as part of supplementary files and the theory we have discussed and everything is implemented for you to play with.

Thank you.